TGU-34
UWThPh-2004-26
hep-ph/0409347

Impact of CP phases on the search for top and bottom squarks [1]

A. Bartl[a], S. Hesselbach[a], K. Hidaka[b], T. Kernreiter[a] and W. Porod[c]

[a] *Institut für Theoretische Physik, Universität Wien, A-1090 Vienna, Austria*
[b] *Department of Physics, Tokyo Gakugei University, Koganei, Tokyo 184–8501, Japan*
[c] *Institut für Theoretische Physik, Universität Zürich, CH-8057 Zürich, Switzerland*

Abstract

We study the decays of top squarks ($\tilde{t}_{1,2}$) and bottom squarks ($\tilde{b}_{1,2}$) in the Minimal Supersymmetric Standard Model (MSSM) with complex parameters A_t, A_b, μ and M_1. We show that including the corresponding phases strongly affects the branching ratios of $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ decays in a large domain of the MSSM parameter space. This could have an important impact on the search for $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ and the determination of the underlying MSSM parameters at future colliders.

[1] Invited talk presented by K. Hidaka in The 12th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY04), June 17-23, 2004, Tsukuba, Japan.

1 Introduction

Many phenomenological studies on SUSY particle searches have been performed in the Minimal Supersymmetric Standard Model (MSSM) with real SUSY parameters. In general, however, some of the SUSY parameters may be complex, in particular the higgsino mass parameter μ, the gaugino mass parameters $M_{1,2,3}$ and the trilinear scalar coupling parameters A_f of the sfermions $\tilde{f}$. The SU(2) gaugino mass parameter M_2 can be chosen real after an appropriate redefinition of the fields. Not only the CP-violating observables (such as fermion EDMs) but also the CP-conserving observables (such as cross sections and decay branching ratios) depend on the phases of the complex parameters, because in general the mass-eigenvalues and the couplings of the SUSY particles involved are functions of the underlying complex parameters. For example, the decay branching ratios of the staus $\tilde{\tau}_{1,2}$ and τ-sneutrino $\tilde{\nu}_\tau$ can be quite sensitive to the complex phases of the stau and gaugino-higgsino sectors [1]. Therefore, in a complete phenomenological analysis of production and decays of the SUSY particles one has to take into account that A_f, μ and $M_{1,3}$ can be complex. In this article based on [2, 3] we study the effects of the phases of A_t, A_b, μ and M_1 on the decay branching ratios of the stops $\tilde{t}_{1,2}$ and sbottoms $\tilde{b}_{1,2}$ with $\tilde{q}_1$ ($\tilde{q}_2$) being the lighter (heavier) squark. We take into account the explicit CP violation in the Higgs sector.

2 SUSY CP Phase Dependences of Masses, Mixings and Couplings

In the MSSM the squark sector is specified by the mass matrix in the basis $(\tilde{q}_L, \tilde{q}_R)$ with $\tilde{q} = \tilde{t}$ or $\tilde{b}$

$$\mathcal{M}^2_{\tilde{q}} = \begin{pmatrix} m^2_{\tilde{q}_L} & a^*_q m_q \\ a_q m_q & m^2_{\tilde{q}_R} \end{pmatrix} \tag{1}$$

with

$$m^2_{\tilde{q}_L} = M^2_{\tilde{Q}} + m^2_Z \cos 2\beta \, (I_3^{q_L} - e_q \sin^2\theta_W) + m^2_q, \tag{2}$$

$$m^2_{\tilde{q}_R} = M^2_{\{\tilde{U},\tilde{D}\}} + m^2_Z \cos 2\beta \, e_q \, \sin^2\theta_W + m^2_q, \tag{3}$$

$$a_q m_q = \begin{cases} (A_t - \mu^* \cot\beta)\, m_t & (\tilde{q} = \tilde{t}) \\ (A_b - \mu^* \tan\beta)\, m_b & (\tilde{q} = \tilde{b}) \end{cases} \tag{4}$$

$$= |a_q m_q| \, e^{i\varphi_{\tilde{q}}} \; (-\pi < \varphi_{\tilde{q}} \le \pi). \tag{5}$$

Here I_3^q is the third component of the weak isospin and e_q the electric charge of the quark q. $M_{\tilde{Q},\tilde{U},\tilde{D}}$ and $A_{t,b}$ are soft SUSY–breaking parameters and $\tan\beta = v_2/v_1$ with v_1 (v_2) being the vacuum expectation value of the Higgs field H_1^0 (H_2^0). We take A_q ($q = t, b$) and μ as complex parameters: $A_q = |A_q| \, e^{i\varphi_{A_q}}$ and $\mu = |\mu| \, e^{i\varphi_\mu}$ with $-\pi < \varphi_{A_q,\mu} \le \pi$. Diagonalizing the matrix (1) one gets the mass eigenstates $\tilde{q}_1$ and $\tilde{q}_2$

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} = R^{\tilde{q}} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix} = \begin{pmatrix} e^{i\varphi_{\tilde{q}}} \cos\theta_{\tilde{q}} & \sin\theta_{\tilde{q}} \\ -\sin\theta_{\tilde{q}} & e^{-i\varphi_{\tilde{q}}} \cos\theta_{\tilde{q}} \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix} \tag{6}$$

with the masses $m_{\tilde{q}_1}$ and $m_{\tilde{q}_2}$ ($m_{\tilde{q}_1} < m_{\tilde{q}_2}$), and the mixing angle $\theta_{\tilde{q}}$

$$
\begin{aligned}
m^2_{\tilde{q}_{1,2}} &= \frac{1}{2}(m^2_{\tilde{q}_L} + m^2_{\tilde{q}_R} \mp \sqrt{(m^2_{\tilde{q}_L} - m^2_{\tilde{q}_R})^2 + 4|a_q m_q|^2}), &(7)\\
\theta_{\tilde{q}} &= \tan^{-1}(|a_q m_q|/(m^2_{\tilde{q}_1} - m^2_{\tilde{q}_R})) \quad (-\pi/2 \le \theta_{\tilde{q}} \le 0). &(8)
\end{aligned}
$$

The $\tilde{q}_L - \tilde{q}_R$ mixing is large if $|m^2_{\tilde{q}_L} - m^2_{\tilde{q}_R}| \lesssim |a_q m_q|$, which may be the case in the $\tilde{t}$ sector due to the large m_t and in the $\tilde{b}$ sector for large $\tan\beta$ and $|\mu|$.

We assume that the gluino mass $m_{\tilde{g}} = M_3$ is real. We write the U(1) gaugino mass M_1 as $M_1 = |M_1|e^{i\varphi_1}$ $(-\pi < \varphi_1 \le \pi)$. Inspired by the gaugino mass unification we take $|M_1| = (5/3)\tan^2\theta_W M_2$ and $m_{\tilde{g}} = (\alpha_s(m_{\tilde{g}})/\alpha_2)M_2$. In the MSSM Higgs sector with explicit CP violation the neutral Higgs mass eigenstates H^0_1, H^0_2 and H^0_3 ($m_{H^0_1} < m_{H^0_2} < m_{H^0_3}$) are mixtures of CP-even and CP-odd states. For the radiatively corrected masses and mixings of the Higgs bosons we use the formulae of Ref.[4].

Possible important decay modes of $\tilde{t}_{1,2}$ are:

$$
\begin{aligned}
\tilde{t}_1 &\to t\tilde{g}\,, t\tilde{\chi}^0_i\,, b\tilde{\chi}^+_j\,, \tilde{b}_1 W^+\,, \tilde{b}_1 H^+ &(9)\\
\tilde{t}_2 &\to t\tilde{g}\,, t\tilde{\chi}^0_i\,, b\tilde{\chi}^+_j\,, \tilde{t}_1 Z^0\,, \tilde{b}_{1,2} W^+\,, \tilde{t}_1 H^0_k\,, \tilde{b}_{1,2} H^+. &(10)
\end{aligned}
$$

Those of $\tilde{b}_{1,2}$ are analogous. The CP phase dependences of the decay widths stems from those of the involved mass-eigenvalues, mixings and couplings among the interaction-eigenfields. In [2, 3] it is found that the masses, mixings and couplings of the involved SUSY particles (stops, sbottoms, charginos $\tilde{\chi}^\pm_i$ ($m_{\tilde{\chi}^\pm_1} < m_{\tilde{\chi}^\pm_2}$), neutralinos $\tilde{\chi}^0_j$ ($m_{\tilde{\chi}^0_1} < ... < m_{\tilde{\chi}^0_4}$), and Higgs bosons) can be very sensitive to the CP phases in a large region of the MSSM parameter space. For the $\tilde{q}_i$ ($\tilde{q} = \tilde{t}, \tilde{b}$) sectors we find:

1. The mass-eigenvalues $m_{\tilde{q}_{1,2}}$ are sensitive to the phases $(\varphi_{A_q}, \varphi_\mu)$ via $\cos(\varphi_{A_q} + \varphi_\mu)$ if and only if $|a_q m_q| \sim (m^2_{\tilde{q}_L} + m^2_{\tilde{q}_R})/2$ *and* $|A_q| \sim |\mu| C_q$ (with $C_t = \cot\beta$ and $C_b = \tan\beta$) (see Eqs. (4),(7)).

2. The $\tilde{q}$-mixing angle $\theta_{\tilde{q}}$ (given by $\tan 2\theta_{\tilde{q}} = 2|a_q m_q|/(m^2_{\tilde{q}_L} - m^2_{\tilde{q}_R})$) is sensitive to $(\varphi_{A_q}, \varphi_\mu)$ via $\cos(\varphi_{A_q} + \varphi_\mu)$ if and only if $2|a_q m_q| \gtrsim |m^2_{\tilde{q}_L} - m^2_{\tilde{q}_R}|$ *and* $|A_q| \sim |\mu| C_q$ (see Eqs. (4),(7), (8)).

3. The $\tilde{q}$-mixing phase $\varphi_{\tilde{q}}$ in Eq.(5) is sensitive to $(\varphi_{A_q}, \varphi_\mu)$, φ_{A_q} and φ_μ if $|A_q| \sim |\mu| C_q$, $|A_q| \gg |\mu| C_q$ and $|A_q| \ll |\mu| C_q$, respectively. For large squark mixing the term $\propto \sin 2\theta_{\tilde{q}} \cos\varphi_{\tilde{q}}$ can result in a large phase dependence of the decay widths [3] (see Eq.(6)).

Therefore, we expect that the widths (and hence the branching ratios) of the $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ decays are sensitive to the phases ($\varphi_{A_{t,b}}$, φ_μ, φ_1) in a large region of the MSSM parameter space.

3 Numerical Results

In order to improve the convergence of the perturbative expansion [5] we calculate the tree-level widths by using the corresponding tree-level couplings defined in terms of "effective" MSSM running quark masses $m^{run}_{t,b}$ (i.e. those defined in terms of the effective running Yukawa couplings $h^{run}_{t,b} \propto m^{run}_{t,b}$). For the kinematics, e.g., for the phase space factor we use the on-shell masses obtained by using the on-shell (pole) quark masses $M_{t,b}$. We take $M_t = 175$ GeV, $M_b = 5$ GeV, $m^{run}_t = 150$ GeV, and $m^{run}_b = 3$ GeV. We fix $|A_t| = |A_b| \equiv |A|$ and $M_2 = 300$ GeV, i.e. $m_{\tilde{g}} = 820$ GeV. In our numerical study we take $\tan\beta$, $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, $m_{\tilde{b}_1}$, $|A|$, $|\mu|$, φ_{A_t}, φ_{A_b}, φ_μ, φ_1 and m_{H^+} as input parameters, where $m_{\tilde{t}_{1,2}}$ and $m_{\tilde{b}_1}$ are the on-shell squark masses. Note that for a given set of the input parameters we obtain two solutions for ($M_{\tilde{Q}}$, $M_{\tilde{U}}$) corresponding to the two cases $m_{\tilde{t}_L} \geq m_{\tilde{t}_R}$ and $m_{\tilde{t}_L} < m_{\tilde{t}_R}$ from Eqs. (1)-(4) and (7) with m_t replaced by M_t. In the plots we impose the conditions as described in [2, 3] in order to respect experimental and theoretical constraints, such as the LEP limits and $b \to s\gamma$ data.

The experimental limits on the EDMs of electron, neutron and ^{199}Hg strongly constrain the SUSY CP phases. Here we adopt the scenario of [6] where the first two generations of the sfermions are very heavy and hence $\varphi_{A_{t,b}}$, φ_μ and φ_1 are practically unconstrained. We have also checked that the electron and neutron EDM constraints at two-loop level [7] are fulfilled in the numerical examples studied in this article.

In Fig.1 we show the φ_{A_t} dependence of the $\tilde{t}_2$ decay branching ratios for $\varphi_\mu = 0$ and $\pi/2$ with $\tan\beta$=8, ($m_{\tilde{t}_1}$,$m_{\tilde{t}_2}$,$m_{\tilde{b}_1}$)=(400,700,200) GeV, $|A| = 800$ GeV, $|\mu| = 500$ GeV, φ_{A_b}=φ_1=0, and $m_{H^+} = 600$ GeV in the case $m_{\tilde{t}_L} \geq m_{\tilde{t}_R}$. The case $m_{\tilde{t}_L} < m_{\tilde{t}_R}$ leads to similar results. We see that the $\tilde{t}_2$ decay branching ratios are very sensitive to φ_{A_t} and depend significantly on φ_μ. For large $\tan\beta$($\gtrsim$ 15) we have obtained results similar to those for $\tan\beta$=8 [2, 3]. For $\tilde{t}_1$ and $\tilde{b}_{1,2}$ decays we have obtained results similar to those for the $\tilde{t}_2$ decays [2, 3]. We have also found that for small $\tan\beta$($\lesssim$ 8) the $\tilde{t}_1$ decay can be fairly sensitive to φ_1 [2].

4 Parameter Determination

We now study to which extent one can extract the underlying MSSM parameters (such as $\tan\beta$, $A_{t,b}$ etc.) from measured observables (such as masses, cross sections and branching ratios). The observables are functions of the MSSM parameters. Therefore, in case the number of measured observables is larger than that of the MSSM parameters, the whole data set of the observables over-constrains the MSSM parameters. In this case the MSSM parameters and their errors can be determined by a χ^2 fit to the experimental data of the observables. In the fit the errors of the observables are propagated to those of the MSSM parameters. The assumptions for the expected experimental errors of the observables measured at TESLA, CLIC and LHC are described in [3]. Our strategy for the parameter determination is as follows:

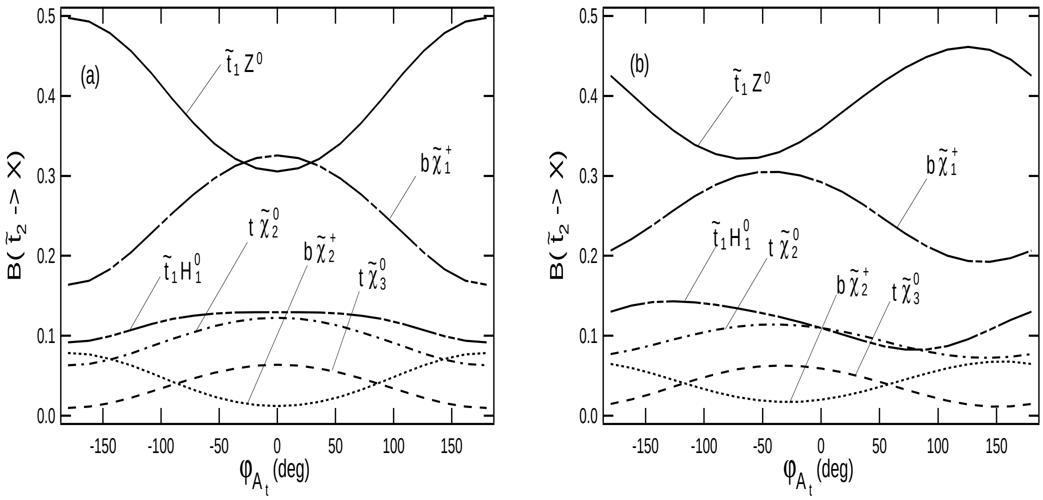

Figure 1: φ_{A_t} dependence of the $\tilde{t}_2$ decay branching ratios for $\varphi_\mu = 0$ (a) and $\pi/2$ (b) with $\tan\beta$=8, ($m_{\tilde{t}_1}$,$m_{\tilde{t}_2}$,$m_{\tilde{b}_1}$)=(400,700,200) GeV, $|A| = 800$ GeV, $|\mu| = 500$ GeV, φ_{A_b}=φ_1=0, and $m_{H^+} = 600$ GeV in the case $m_{\tilde{t}_L} \geq m_{\tilde{t}_R}$. Note that the $\tilde{t}_1 H^0_{2,3}$ and $\tilde{b}_1 H^+$ modes are kinematically forbidden here.

1. Take a specific set of values of the underlying MSSM parameters.
2. Calculate the masses of $\tilde{t}_i$, $\tilde{b}_i$, $\tilde{\chi}^0_j$, $\tilde{\chi}^\pm_k$, H^0_ℓ, the production cross sections for $e^+e^- \to \tilde{t}_i\bar{\tilde{t}}_j$, and $e^+e^- \to \tilde{b}_i\bar{\tilde{b}}_j$, and the branching ratios of the $\tilde{t}_i$ and $\tilde{b}_i$ decays, and estimate the expected experimental errors of these observables.
3. Regard these calculated values as real experimental data with definite errors.
4. Determine the underlying MSSM parameters and their errors from the "experimental data" by a χ^2 fit.

We consider two scenarios, one with small $\tan\beta$ and one with large $\tan\beta$. The small $\tan\beta$ scenario is characterized by the following underlying MSSM parameters: $M_{\tilde{D}} = 169.6$ GeV, $M_{\tilde{U}} = 408.8$ GeV, $M_{\tilde{Q}} = 623.0$ GeV, $|A_t| = |A_b| = 800$ GeV, $\varphi_{A_t} = \varphi_{A_b} = \pi/4$, $\varphi_1 = 0$, $M_2 = 300$ GeV, $\mu = -350$ GeV, $\tan\beta = 6$, $m_{\tilde{g}} = 1000$ GeV, and $m_{H^\pm} = 900$ GeV. (Here we do not assume the unification relation between $m_{\tilde{g}}$ and M_2.) The large $\tan\beta$ scenario is specified by: $M_{\tilde{D}} = 360.0$ GeV, $M_{\tilde{U}} = 198.2$ GeV, $M_{\tilde{Q}} = 691.9$ GeV, $|A_t| = 600$ GeV, $\varphi_{A_t} = \pi/4$, $|A_b| = 1000$ GeV, $\varphi_{A_b} = 3\pi/2$, $\varphi_1 = 0$, $M_2 = 200$ GeV, $\mu = -350$ GeV, $\tan\beta = 30$, $m_{\tilde{g}} = 1000$ GeV, and $m_{H^\pm} = 350$ GeV. The resulting values of the observables and their expected experimental errors are shown for the two scenarios in [3]. We regard these calculated values as real experimental data with definite errors. We determine the underlying MSSM parameters and their errors from the "experimental data" on these observables by a χ^2 fit. The results obtained are shown in Table 2 of [3]. As one can see, all parameters except A_b can be determined rather precisely. $\tan\beta$ can be determined with an error of about 3% in both scenarios. The relative error of the squark mass parameters

squared $M^2_{\tilde{Q},\tilde{U},\tilde{D}}$ is in the range of 1% to 2%. $Re(A_t)$ and $Im(A_t)$ can be measured within an error of $2-3\%$ independently of $\tan\beta$. The situation for A_b is considerably worse: in case of small $\tan\beta$ one gets only an order of magnitude estimate. The reason is that both the bottom squark mixing angle and the bottom squark couplings depend only weakly on A_b for small $\tan\beta$. In case of large $\tan\beta$ the situation improves somewhat in particular for the imaginary part of A_b. A χ^2 fit using only real MSSM parameters would result in a totally wrong parameter determination with a significantly larger value of χ^2. We have found that the analogous fit procedure using only real MSSM parameters gives a much larger value for χ^2: $\Delta\chi^2 = 286.6$ with DOF=61 for the scenario with $\tan\beta = 6$ and $\Delta\chi^2 = 22.5$ with DOF=61 for the scenario with $\tan\beta = 30$, where DOF is 'degree of freedom'.

5 Conclusion

We have studied the decays of $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ in the MSSM with complex parameters $A_{t,b}, \mu$ and M_1. We have shown that including the CP phases strongly affects the branching ratios of $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ decays in a large domain of the MSSM parameter space. This could have an important impact on the search for $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ and the determination of the underlying MSSM parameters at future colliders.

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